

Structure of the exotic nucleus ^{14}B in the ground state

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Abstract

We investigate the structure of the neutron rich nucleus ^{14}B through studies of its breakup in the Coulomb field of a heavy target. The breakup amplitude is calculated within an adiabatic as well as finite range DWBA theories of breakup reactions. Both these formalisms allow the use of realistic wave functions for the relative motion between the fragments in the ground state of the projectile. The longitudinal momentum distributions of ^{13}B (ground state) following the breakup of ^{14}B on a heavy target at beam energy of 60 MeV/nucleon, calculated using two possible ground state configurations of ^{14}B , have been compared with the recent data. The data seem to favour $^{13}\text{B}(\frac{3}{2}^-) \otimes 2s_{1/2}$ as the possible ground state configuration of ^{14}B with a spectroscopic factor close to unity. We give our predictions for the neutron angular distributions and the relative energy spectra in the one-neutron removal reaction of ^{14}B .

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It has now been well established that close to the neutron drip line, one encounters nuclei which have a long tail of one or two neutrons outside a nuclear core – a feature commonly known as a neutron halo [1]. It has been observed that nuclei with a dominant configuration of loosely bound s -wave valence neutron(s) generally have a well-developed halo structure. Breakup reactions, in which the halo particle is removed from the system, are promising tools in investigating the structure of these nuclei. Thus, halo formation in such nuclei can be investigated by measuring the longitudinal or parallel momentum distribution (PMD) of fragments from the breakup reaction [2]. The wide spatial dispersion characteristic of a halo neutron translates into a narrow momentum distribution.

Early experiments on breakup reactions were based on the assumption that the measured momentum distribution represented a single reaction channel. It has recently become possible to go beyond this simple approach by measuring the γ -radiation from the decay of excited states of the core in coincidence with the breakup fragments [3]. Thus breakup events, in which the core remains in the ground state, are identified by associating them with measured γ -ray multiplicity equal to zero. This technique, therefore, allows for spectroscopic investigation of both the core nucleus and the valence nucleon, by measuring the partial cross sections for the excitation of different final states of the core.

Among the candidates for neutron halo nuclei, the ^{14}B nucleus (with valence neutron separation energy of 0.97 MeV) is of particular interest as it is the lowest mass bound system among the $N=9$ isotones. The well-known halo nuclei ^{11}Be , ^{11}Li , ^{14}Be , ^{17}B and ^{19}C occupy a similar position for $N=7$, $N=8$, $N=10$, $N=12$ and $N=13$ respectively. Moreover, ^{14}B is an odd-odd nucleus and thus different from any other neutron halo system observed to date.

Moderate enhancements have been observed in the total reaction cross section measurements for ^{14}B at intermediate energies [4,5], thereby giving it a large root mean square (rms) radius. Non-linear relativistic mean field calculations predict inversion of $1d_{5/2}$ and $2s_{1/2}$ orbitals (as in the case of the well-established one-neutron halo nucleus ^{11}Be) in the ground state of ^{14}B [6]. Very recent measurement at GANIL on the core PMD resulting from the one-neutron removal reaction of ^{14}B on a carbon target at 50 MeV/nucleon incident energy gives a narrow width (FWHM = 56.5 ± 0.5 MeV/c) [7], which is a characteristic of the halo structure. All these facts indicate the possibility of the presence of an extended neutron distribution in this nucleus, although the one-neutron separation energy of almost 1 MeV is likely to suppress the development of as large a distribution as that found in the more weakly bound one-neutron halo nuclei ^{11}Be and ^{19}C . It should, however, be noted that ^{15}C has a valence neutron separation energy of $\simeq 1.2$ MeV, which is even larger than that of ^{14}B . But it is most likely a one-neutron halo nucleus [8], because the valence neutron has a dominant s -state configuration in the ground state of ^{15}C . On the other hand, although the one-neutron separation energy in case of ^{17}C is only 0.729 MeV, the halo formation in this nucleus is hindered because of a strong d -wave configuration of the valence neutron in its ground state [2,8].

Recently the PMD's of the ^{13}B core fragment have been measured in one-neutron knock-out reactions from ^{14}B on both light (^9Be) and heavy (^{197}Au) targets at around 60 MeV/nucleon beam energy at MSU [9]. Calculations on the parallel momentum distributions, when ^{13}B remains in its ground state, have been compared with the data for both the targets [9]. The agreement between the calculated width and experimental width

(59 ± 3 MeV/c) has been found to be consistent with expectations for a dominant weakly bound $2s_{1/2}$ neutron configuration, which lends support to the existence of a one-neutron halo structure in ^{14}B .

The mechanism of the breakup reaction of the loosely bound exotic nuclei on heavy targets is generally known to be dominated by Coulomb dissociation, particularly below the grazing angle. The grazing angle for the MSU reaction on Au target is around 4.4° . The angular acceptances for detection of the charged ^{13}B core were $\pm 3.5^\circ$ and $\pm 5^\circ$ in the dispersive and non-dispersive directions. Therefore, it is expected that the heavy target data have mostly contributions from the Coulomb dissociation.

Using a Yukawa potential with finite-size corrections for the core-neutron relative motion wave function, the authors of Ref. [9] performed semiclassical calculations for Coulomb breakup of ^{14}B on the Au target and compared their results with the data for the events in which the core remains in the ground state. The total one-neutron removal cross section of 543 mb calculated by them is somewhat less than the measured cross section of 638 ± 45 mb. The calculated PMD had to be normalized (by a factor greater than unity) to the experimental data in order to get a fit [9]. However, the agreement in the wings of the distribution was still unsatisfactory. The zero-range calculations done in Ref. [9] also does not allow one to draw inference on spectroscopic factors of the possible configurations present in the ground state of ^{14}B , as far as the data on the heavy target is concerned.

In this Brief Report, we perform Coulomb breakup calculations on the PMD of ^{13}B (ground state) resulting from the breakup of ^{14}B on Au and compare the results with the MSU data with a view to put constraint on the spectroscopic informations of the probable configurations in the ground state of ^{14}B . We use two distinct theoretical approaches - the adiabatic (AD) model [10–12] and the finite range (post form) distorted wave Born approximation (FRDWBA) method [8]. They give almost the same expression for the reaction amplitude, but differ in details of the formulation. The adiabatic theory of the Coulomb breakup of a projectile used by us has been described extensively in [10–12]. The triple differential cross section for the reaction, in which a projectile a breaks up into a charged core c and a neutral valence particle n on target t , is given by (assuming an inert core)

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_n} = \frac{2\pi}{\hbar v_a} \left\{ \sum_{l\mu} \frac{1}{(2l+1)} |\beta_{l\mu}^{\text{AD}}|^2 \right\} \rho(E_c, \Omega_c, \Omega_n) . \quad (1)$$

Here v_a is the a - t relative velocity in the entrance channel and $\rho(E_c, \Omega_c, \Omega_n)$ the phase space factor appropriate to the three-body final state. The reduced amplitude $\beta_{l\mu}^{\text{AD}}$ is given by

$$\beta_{l\mu}^{\text{AD}} = \langle \mathbf{q}_n | V_{cn} | \Phi_a^{l\mu} \rangle \langle \chi^{(-)}(\mathbf{k}_c); \alpha \mathbf{k}_n | \chi^{(+)}(\mathbf{k}_a) \rangle . \quad (2)$$

The first term in Eq. (2) contains the structure information about the projectile through the ground state wave function $\Phi_a^{l\mu}(\mathbf{r})$, and it is known as the vertex function [11], while the second term is associated only with the dynamics of the reaction, which can be expressed in terms of the bremsstrahlung integral [13]. For explanation of other quantities in the above equation, we refer to [11]. It should, however, be mentioned that to obtain Eq. (2) [10], it has been assumed that the dominant projectile breakup configurations excited are in the low-energy continuum (the adiabatic approximation).

For the FRDWBA case, the triple differential cross section looks the same excepting the reduced amplitude, which is given by

$$\beta_{l\mu}^{\text{FRDWBA}} = \langle (\gamma \mathbf{q}_n - \alpha \mathbf{K}) | V_{cn} | \Phi_a^{l\mu} \rangle \langle \chi^{(-)}(\mathbf{k}_c); \delta \mathbf{k}_n | \chi^{(+)}(\mathbf{k}_a) \rangle . \quad (3)$$

In the above, \mathbf{K} is an effective local momentum associated with the core-target relative system, whose direction has been taken to be the same as the direction of the asymptotic momentum \mathbf{q}_c [8]. For clarifications about other quantities, we refer to [8].

Both the theories are fully quantum mechanical. The adiabatic formalism is non-perturbative, while the FRDWBA formalism assumes that the breakup states are weakly coupled. Both the methods retain finite-range effects associated with the interaction between the breakup fragments and include the initial and final state Coulomb interactions to all orders. The theories allow the use of wave functions of any relative orbital angular momentum l for the motion between c and n in the ground state of a .

The spin-parity of ^{14}B is known to be 2^- in its ground state. Shell model calculations with the WBP and WBT residual interactions suggest spectroscopic factors of 0.306 and 0.662 respectively for the removal of a valence neutron from the $1d_{5/2}$ and $2s_{1/2}$ states in ^{14}B [14]. For our calculations, we have used a single particle potential model for ^{14}B in which the valence neutron, with a binding energy of 0.97 MeV, moves relative to the ^{13}B core (with intrinsic spin-parity $\frac{3}{2}^-$) in a Woods-Saxon potential with radius and diffuseness parameters 1.15 fm and 0.5 fm respectively. The depths of this potential well have been adjusted to reproduce the valence neutron binding energy. We have considered two possible configurations for the valence neutron in the ^{14}B ground state: (a) a $2s_{1/2}$ state bound to the ^{13}B core and (b) a $1d_{5/2}$ state bound to the ^{13}B core. The rms sizes of ^{14}B with options (a) and (b) were found to be 2.79 fm and 2.57 fm respectively, while the corresponding rms sizes of the valence neutron were 5.46 fm and 3.43 fm respectively. The rms size used for the ^{13}B core is 2.5 fm [15].

In Fig. 1, we have compared our calculations with the data for the PMD of ^{13}B (ground state) in the breakup of ^{14}B on Au at 60 MeV/nucleon beam energy. In these calculations, the maximum values of the core transverse momentum integrations correspond to the maximum angles of detection of the core as in the MSU experiment [9]. Calculations corresponding to pure s -state and pure d -state configurations of the valence neutron are shown by the solid and dashed lines respectively, while a coherent superposition of these two results weighted by the spectroscopic factors of Ref. [14] is given by the long-dashed curve. The AD model results are given by thick lines, whereas those of FRDWBA by thin lines. This same convention has been followed in case of subsequent figures also. We see that both the theories give similar results. The pure d -state contribution is much less than the pure s -state one. The calculated width for the pure s -state result is about 95% of the measured width of 59 ± 3 MeV/c, with the experimental error of $\pm 5\%$ [16]. It gives almost 80% of the total one-neutron removal cross section, which is 510.4 mb [16]. But the fit to the experimental data worsens if we consider a non-negligible $l=2$ admixture in the wave function of ^{14}B (long-dashed curves), taking the spectroscopic factors of the s -state and d -state neutrons as in Ref. [14]. In any case, the theoretical cross section is less than the experimental one.

The binding energy of the valence neutron(s) plays a crucial role in determining the relative importance of Coulomb and nuclear breakup cross sections of the halo nuclei in different kinematical domains. It has been found in case of ^6He , with a separation energy

of 0.975 MeV for the valence neutrons, that the nuclear breakup contributions could be substantial just around and above the grazing angle [17]. The one-neutron separation energy in ^{14}B is almost 1 MeV. Since the upper limits of detection angles in the MSU data were around or slightly above the grazing angle, it is possible that some contribution from nuclear breakup effects is also present in the above data. This could be the reason for the calculated results being smaller than the experimental ones.

We expect that breakup observables measured at very forward angles (below the grazing angle) will not be affected by strong interactions and also Coulomb-nuclear interference for this exotic nucleus. In Fig. 2, we have shown the calculated results for the ^{13}B (ground state)- n relative energy spectra for the same reaction considered above. The angular integration for the scattering of the projectile-target relative system in final channel has been performed up to the grazing angle of 4.4° . The AD and FRDWBA theories again give almost the same results. The pure s -state energy spectra (solid lines) have a strong peak at very low relative energy around 0.4 MeV. This is very much characteristic of the halo nuclei for breakup on a heavy target [18]. The d -state spectra (dashed lines) are almost two orders of magnitude smaller than the s -state spectra. We also show the coherent sum of the two separate contributions weighted by the spectroscopic factors of Ref. [14] by the long-dashed lines. This also has a prominent peak around 400 keV relative energy. Since nuclear breakup effects could be important at relative energies around and beyond 1 MeV [12,19], we suggest that measurements be done at small relative energies.

The exclusive neutron angular distribution in the one-neutron removal reaction on a heavy target has been found to be very much forward peaked for the one-neutron halo nuclei [20]. This is a definite indication of the presence of a neutron halo structure. Therefore, we give predictions for the exclusive neutron angular distribution for the same above reaction in Fig. 3. The angular integration with respect to the core fragment has been done up to 4.4° . The results for the pure s -state (solid lines) and coherent sum of s - and d -state contributions weighted by the same spectroscopic factors (long-dashed lines) are almost the same within both the formalisms. The pure d -state results (dashed lines) are slightly different at very forward angles. Here also the pure d -state contributions are two orders of magnitude smaller than the pure s -state ones. But none of these distributions is quite forward peaked. Nevertheless, these results together with the above predictions will prove useful in getting structure informations about the ground state of ^{14}B .

In conclusion, we have studied Coulomb breakup of the neutron rich exotic nucleus ^{14}B and compared our calculations with the recently available experimental data on a heavy target in order to put constraint on the spectroscopic factors of its possible ground state configurations. The breakup amplitude is calculated within two approximate quantum mechanical theoretical models. The adiabatic model assumes that the important excitations of the projectile are to the low-energy continuum so that they can be treated adiabatically. The distorted wave Born approximation method, on the other hand, assumes that the breakup states are weakly coupled. Both the methods permit finite-range treatment of the projectile vertex and include initial and final state Coulomb interactions to all orders.

Using a single particle potential model for ^{14}B , we find that calculations using the configuration $^{13}\text{B}(\frac{3}{2}^-) \otimes 2s_{1/2}$ for the ground state of ^{14}B with a spectroscopic factor ≈ 1 come closest to the MSU data on parallel momentum distribution of ^{13}B (ground state) resulting from the fragmentation of ^{14}B . This is true within both the formalisms. This gives support

to the existence of a one-neutron halo structure in ^{14}B . The small discrepancy between the magnitudes of the theoretical and experimental cross sections could be attributed to the presence of nuclear breakup contribution present in the kinematical domain covered by the data. As far as Coulomb dissociation is concerned, it is suggested that further measurements on breakup on heavy targets at extreme forward angles (below the grazing angle) are necessary to derive very precise spectroscopic informations about the two possible configurations in the ground state of ^{14}B considered in this work. With this end in view, we have given predictions for the exclusive neutron angular distribution and core-valence relative energy spectrum in the one-neutron removal Coulomb breakup reaction of ^{14}B on a heavy target when the core remains in the ground state.

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FIGURES

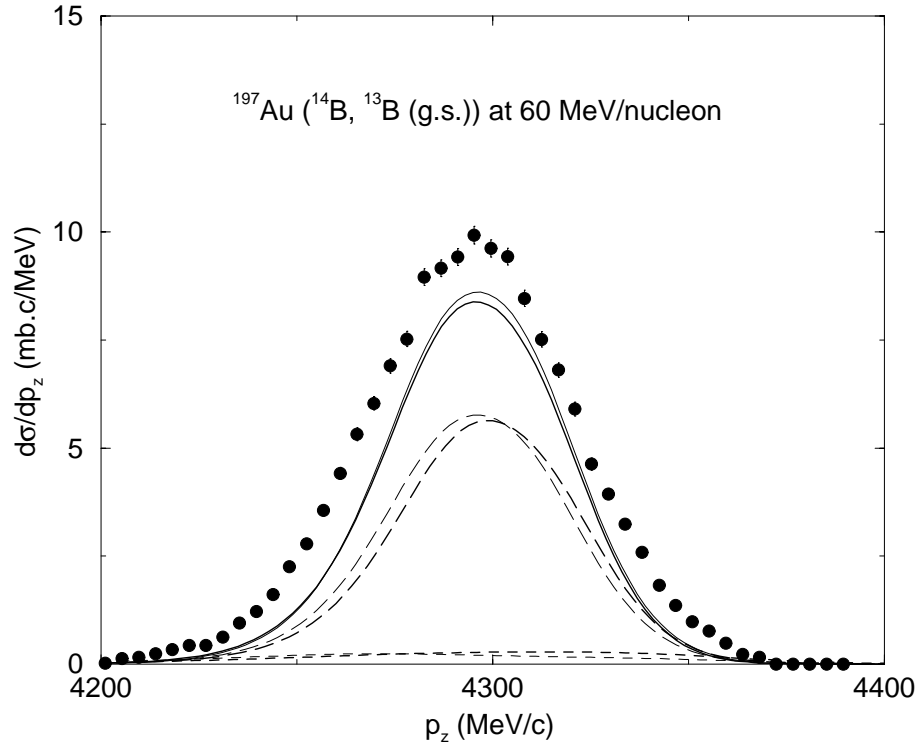


FIG. 1. Calculated parallel momentum distributions of ^{13}B (ground state) for the Coulomb breakup of ^{14}B on Au at 60 MeV/nucleon beam energy. The solid and dashed lines give pure s -state and pure d -state contributions respectively, while the long-dashed curves are the results of coherent superposition of these two contributions weighted by spectroscopic factors given in Ref. [14]. The thick and thin sets of lines are results of calculations of AD and FRDWBA theories respectively. The data have been reported in Ref. [9].

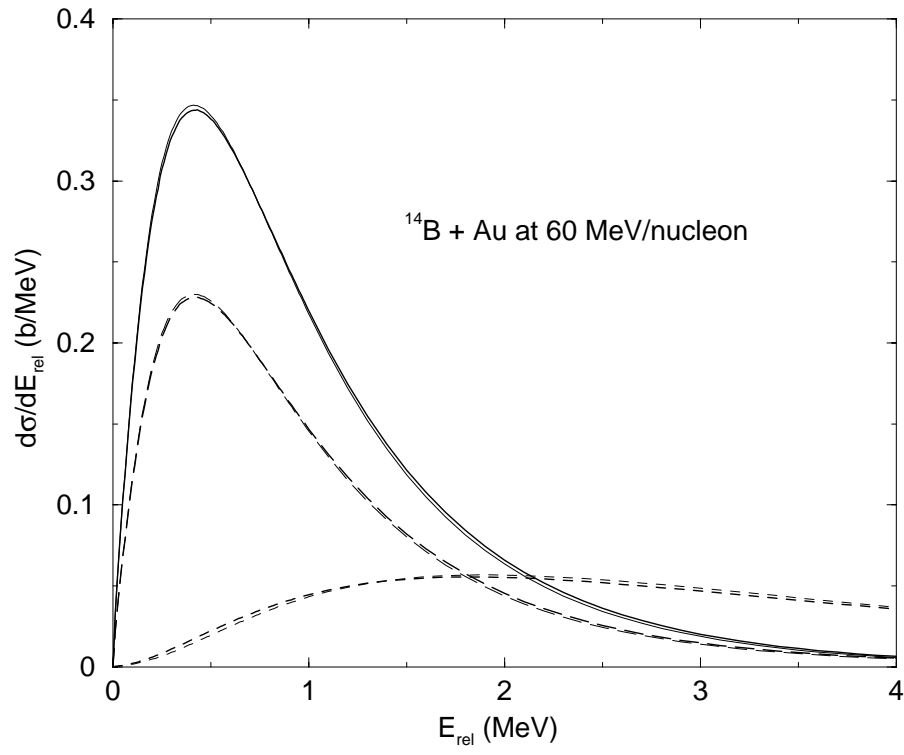


FIG. 2. Calculated core (ground state) - valence neutron relative energy spectra for the Coulomb breakup of ^{14}B on Au at 60 MeV/nucleon beam energy. The solid and dashed lines give pure s -state and (multiplied by 10) pure d -state contributions respectively, while the long-dashed curves are the results of coherent superposition of these two contributions weighted by spectroscopic factors given in Ref. [14]. The thick and thin sets of lines are results of calculations of AD and FRDWBA theories respectively.

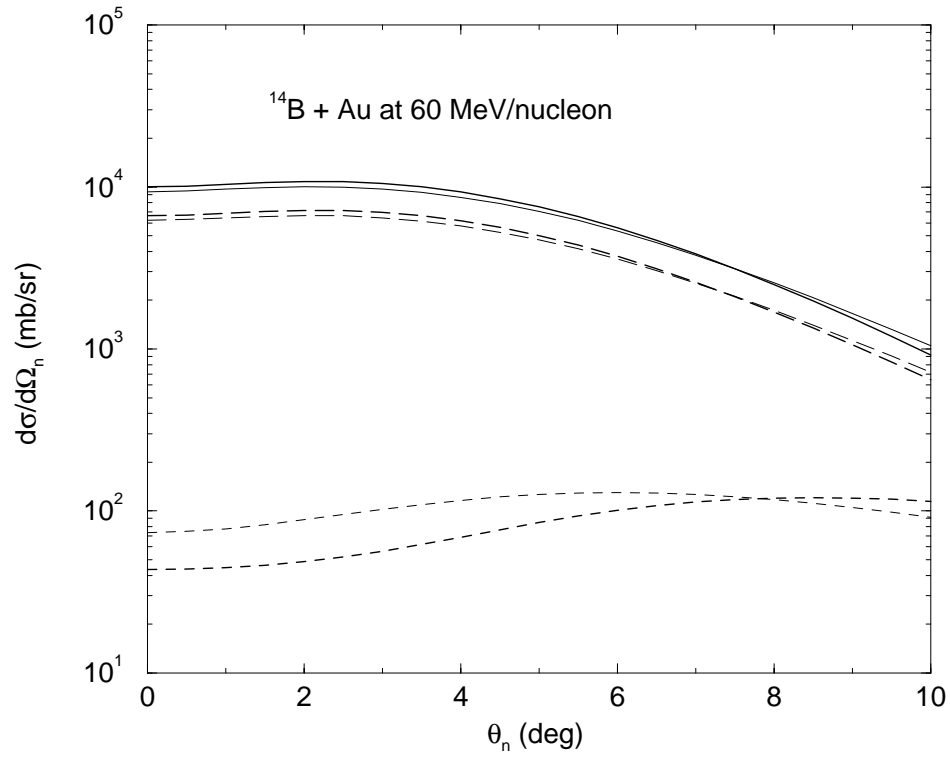


FIG. 3. Calculated exclusive neutron angular distributions for the Coulomb breakup of ^{14}B on Au at 60 MeV/nucleon beam energy when the ^{13}B core remains in the ground state. The solid and dashed lines give pure s -state and pure d -state contributions respectively, while the long-dashed curves are the results of coherent superposition of these two contributions weighted by spectroscopic factors given in Ref. [14]. The thick and thin sets of lines are results of calculations of AD and FRDWBA theories respectively.